Solutions for Minimum Required Forward Link Channel Powers in CDMA Cellular and PCS Systems

Jhong Sam Lee and Leonard E. Miller

Abstract: New solutions are given for the minimum required transmitter powers for CDMA cellular or PCS systems for all categories of the forward link channels, namely pilot, sync, paging, and traffic channels. Any excess power over that required for the specified error performance of any channel category always reduces the user capacity, so it is necessary to know the minimum required power levels for all of the forward link channels. We show the solutions for the forward link channel powers by including fade margins to improve link reliability in lognormal shadowing. The amount of margin required to achieve a given reliability is calculated. We derive system capacity expressions as functions of link margins for specified reliability requirements and the corresponding minimum transmitter power levels. Example solutions are also presented in graphical forms for typical realistic operational parameters, to illustrate the use of the solution formulas. These solutions can be applied to maximize the capacity of a particular CDMA cellular or PCS system under different parametric situations.

Index Terms: CDMA, power control, forward link, reliability.

I. INTRODUCTION

The signal received by a mobile user on the forward link of a cellular or PCS system is subject to level fluctuations due to fading and shadowing. Fading refers to the change in signal level that occurs as two or more signal multipath components, when present, constructively or destructively interfere, depending on the relationship among their carrier phases that is a function of the mobile receiver's motion; the effects of fading are usually characterized by a probability distribution for the received signal level, such as the Rayleigh distribution. Shadowing refers to the variation in the signal level because the propagation loss changes as natural and manmade obstacles affect the signal reception differently in different mobile receiver locations; shadowing is usually modeled as having a lognormal probability distribution [1], [2] whose median is a function of the link distance. The effects of fading can be mitigated by the use of diversity or by increasing the transmitter power to ensure that the average received signal power is sufficient to achieve the desired link error probability performance. The effects of shadowing can be countered by dynamic power control.

For forward link power control schemes for cellular systems, previous studies [3]–[6] considered only the traffic channels and ignored the signaling channels. It is well known that the allocations of the necessary (minimum) transmitter power to signals directed to individual mobile users are interdependent because the signals act as co-channel interference to each other, and hence algorithms for power control must consider joint solutions for the user signal powers. Frequent adjustments to the powers are needed to adapt in real time to shadowing fluctuations. Adaptive power control requires feedback, which is easily incorporated into the full-duplex traffic channels but not usually feasible for the one-to-many signaling channels.

It is known [1] that the propagation loss has a Gaussian distribution when expressed in dB units, given by

$$\begin{aligned} \mathrm{L}\,(\mathrm{dB}) &= \mathrm{G}\left(\mathrm{L}_{med}\,(\mathrm{dB})\,,\,\sigma_{dB}^2\right) \\ &= \mathrm{L}_{med}\,(\mathrm{dB}) + \sigma_{dB}\mathrm{G}\,(0,\,1)\,, \end{aligned} \tag{1a}$$

where $\mathrm{G}(\mu,\,\sigma^2)$ denotes a Gaussian random variable with mean μ and variance σ^2, $\mathrm{L}_{med}\,(\mathrm{dB})$ denotes the median loss as a function of the distance from the base station, and σ_{dB} is the standard deviation of the loss in dB. For a Gaussian distribution, the mean and median are identical. Thus the loss in dB has the probability density function (pdf)

$$\begin{aligned} \mathrm{p}_{\mathrm{L(dB)}}\,(x) &= \frac{1}{\sigma_{dB}}\,\mathrm{p}_{\mathrm{G}}\left(\frac{x-\mathrm{L}_{med}\,(\mathrm{dB})}{\sigma_{dB}}\right) \\ &= \frac{1}{\sigma_{dB}\sqrt{2\pi}}\exp\left\{-\frac{(x-\mathrm{L}_{med}\,(\mathrm{dB}))^2}{2\sigma_{dB}^2}\right\}. \end{aligned} \tag{1b}$$

In absolute units, the propagation loss is the random variable L given by

$$\begin{aligned} \mathrm{L} &= 10^{\mathrm{L(dB)}/10} \\ &= 10^{[\mathrm{L}_{med}(\mathrm{dB})+\sigma_{dB}\mathrm{G}(0,\,1)]/10} \\ &= \mathrm{L}_{med}\cdot 10^{\sigma_{dB}\mathrm{G}(0,1)/10}. \end{aligned} \tag{1c}$$

When a Gaussian random variable is the exponent of any constant, such as e or 10, the resulting random variable is a *lognormal* random variable. Clearly, (1c) fits this description. This is the basis for describing the loss as lognormal in the mobile environment. The pdf of the lognormal random variable L in (1c) is given by

$$\begin{aligned} \mathrm{p}_{\mathrm{L}}\,(x) &= \frac{1}{\beta\,x}\,\mathrm{p}_{\mathrm{L(dB)}}\left(\frac{ln\,x}{\beta}\right) \\ &= \frac{1}{\sigma_{dB}\sqrt{2\pi}\,\beta\,x}\exp\left\{-\frac{[ln\,(x/\mathrm{L}_{med})]^2}{2\beta^2\sigma_{dB}^2}\right\}, \end{aligned} \tag{1d}$$

where $\beta \triangleq (ln\,10)\,/10$. The pdf of the normalized random variable $V = \mathrm{L}/\mathrm{L}_{med} = 10^{\sigma_{dB}\mathrm{G}(0,1)/10}$ is plotted in Fig. 1. Note

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J. S. Lee is with Hung Chang Co. Ltd., Seoul, Korea, e-mail: jsl@hungchang.com.

L. E. Miller is with J.S.Lee Associates, Inc., Rockville, MD, e-mail: Len_Miller@compuserve.com.

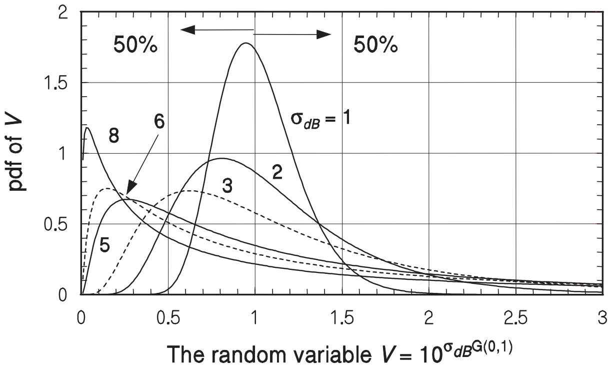

Fig. 1. Probability density function of the normalized lognormal random variable V for $\sigma_{dB} = 1, 2, 3, 5, 6, 8$.

that the median value of V is $10^{[\text{median of } G(0,1)]/10} = 10^0 = 1$. Note also from Fig. 1 that the median of the normalized lognormal random variable is always 1, regardless of the value of σ_{dB}. The median value of lognormal random variable is an important parameter in the discussion of the propagation of forward link signals in the mobile channel.

In this paper, for the forward link of a CDMA cellular [7] or PCS [8] system, on which the channels are orthogonally multiplexed using Walsh functions, we consider power allocation and control techniques not only for the traffic channels of active users but also for the signaling channels that are broadcast continually and monitored by all users, whether active or not. We assume that the system adaptively controls the forward link power on individual traffic channels, based on measurements of signal quality reported to the base station on the reverse link, as described in Section 7.6.4.1.1 of [7]. Based on this assumption, we model a "forward link power control factor" and solve explicitly for the required median values of power for each category of forward link channel. We use these solutions to show inherent limitations on forward link capacity and the dynamic dependence of channel powers and power fractions on the number of active users.

Because the propagation loss is random, so also is the received SNR. The link reliability for the jth channel may be defined as the probability that the actual signal power-to-noise power ratio, SNR, for the channel exceeds the requirement:

$$P_{rel}(j) = \Pr\left\{(\mathrm{SNR})_j > (\mathrm{SNR})_{j,req}\right\}, \tag{2a}$$

where

$$j = 1(\text{pilot}), 2(\text{sync}), 3(\text{paging}), 4\ (\text{traffic}). \tag{2b}$$

In the absence of multiple-access interference, and ignoring miscellaneous link gains and losses, the received SNR in dB can be written

$$\begin{aligned}(\mathrm{SNR})_j &\\ &= \mathrm{P}_j\,(\mathrm{dBm}) - \mathrm{L}\,(\mathrm{dB}) - N_m\,(\mathrm{dBm})\\ &= \mathrm{P}_j\,(\mathrm{dBm}) - [\mathrm{L}_{med}\,(\mathrm{dB}) + \sigma_{dB}\mathrm{G}\,(0,1)] - N_m\,(\mathrm{dBm})\\ &= (\mathrm{SNR})_{j,med} - \sigma_{dB}\mathrm{G}\,(0,1)\,,\end{aligned} \tag{2c}$$

where P_j (dBm) is the transmitter power in dBm, N_m (dBm) is the receiver noise power in dBm, and

$$(\mathrm{SNR})_{j,med} \triangleq \mathrm{P}_j\,(\mathrm{dBm}) - \mathrm{L}_{med}\,(\mathrm{dB}) - N_m\,(\mathrm{dBm}) \tag{2d}$$

is the median received SNR. Let us define the link margin in dB as

$$\mathrm{M}_j\,(\mathrm{dB}) \triangleq (\mathrm{SNR})_{j,med} - (\mathrm{SNR})_{j,req} \tag{2e}$$

which is the amount by which the median received SNR exceeds the required SNR. Substituting (2c) in (2a), we have

$$\begin{aligned}P_{rel}(j) &= \Pr\left\{(\mathrm{SNR})_{j,med} - \sigma_{dB}\mathrm{G}\,(0,1) > (\mathrm{SNR})_{j,req}\right\}\\ &= \Pr\left\{\mathrm{G}\,(0,1) < \frac{(\mathrm{SNR})_{j,med} - (\mathrm{SNR})_{j,req}}{\sigma_{dB}}\right\}\\ &= 1 - \mathrm{Q}\left(\frac{\mathrm{M}_j\,(\mathrm{dB})}{\sigma_{dB}}\right),\end{aligned} \tag{2f}$$

where $\mathrm{Q}(x)$ is the Gaussian Q-function:

$$\mathrm{Q}\,(x) \triangleq \int_x^\infty \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{y^2}{2}\right\} dy. \tag{2g}$$

Thus for the nonadaptive signaling channels and for imperfect power control on the traffic channels, to achieve high link reliability in lognormal shadowing it is necessary to transmit powers, with margin, that are higher than those needed to meet requirements without shadowing. In this paper, we consider multiple-access interference in the formulation of the link reliability for forward links and will show that there are limits on the amount of margin that can be used in a CDMA cellular system. The margins that are used below such limits, however, do provide sufficiently high link reliability for most practical purposes.

II. SOLUTION FOR CDMA FORWARD LINK CHANNEL POWERS

The forward link in the IS-95 CDMA cellular system [7]features four different kinds of channel: (1) a continuously transmitted CDMA pilot channel that provides a PN code reference; (2) a continuously transmitted sync channel that provides base station identification and a system timing reference; (3) up to seven paging channels that inform mobiles of incoming calls and other call-related information and instructions; and (4) traffic channels over which digital voice and other data are transmitted during calls. These channels are transmitted by the base station on the same PN code-modulated RF carrier using Walsh function orthogonal multiplexing. Because the forward link channels are simultaneously transmitted on the same carrier, they share link power budget gain and loss parameters. However, the channel categories have different baseband data rates and different SNR requirements, and the base station transmits each type of channel at a different power level to meet those requirements.

The SNR requirements[1] for the pilot, sync, paging, and traffic channels are expressed as a threshold for the received channel $\mathrm{E}_b/\mathcal{N}_{0,T}$ ($\mathrm{E}_c/\mathcal{N}_{0,T}$ for the pilot channel), where E_b is the

[1] In this paper, we use the term SNR and the energy per bit-to-noise density ratio interchangeably for convenience.

channel bit energy, $\mathcal{N}_{0,T} = \mathcal{N}_0 + \mathcal{I}_{0,T}$ is the effective noise-plus-interference spectral power density, $\mathcal{N}_0$ is the thermal noise spectral power density, and $\mathcal{I}_{0,T}$ is effective interference spectral power density. Assuming the spread spectrum bandwidth equals the chip rate; i.e., $W = R_c$, the received channel $\mathrm{E}_b/\mathcal{N}_{0,T}$ is:

$$\begin{aligned}\left(\frac{\mathrm{E}_b}{\mathcal{N}_{0,T}}\right)_j &= \frac{\mathrm{S}_j\, T_{bj}}{\mathcal{N}_0 + \mathcal{I}_{0,T}} \\ &= \frac{\mathrm{S}_j}{N_m + I_T}\cdot\frac{W}{R_{bj}} \\ &= \frac{\mathrm{S}_j}{N_m + I_T}\cdot(\mathrm{PG})_j\,,\end{aligned} \tag{3a}$$

where

$$\begin{aligned}\mathrm{S}_j &= \text{received power for channel category } j,\\ T_{bj} &= \text{bit period for channel category } j,\\ R_{bj} = 1/T_{bj} &= \text{bit rate for channel category } j,\end{aligned}$$

and the processing gain for channel category j is

$$(\mathrm{PG})_j \triangleq \frac{W}{R_{bj}}, \qquad j\text{=1, 2, 3, 4.} \tag{3b}$$

Note that for the pilot channel, $(\mathrm{PG})_1 = 1$ since the effective bit rate equals the chip rate.

A. Interference Terms

The total interference power on the forward link, I_T, is a component of the SNRs of all the channels and may be broken down into same-cell interference power I_{sc} and other-cell interference power I_{oc}.

The forward link channels are transmitted orthogonally, and thus there is no same-cell multiple-access interference when there is no multipath. However, multipaths do exist in the mobile channel environment and, therefore, there is same-cell forward link interference. Let the received power from all channels in the absence of interference be denoted S; then, the same-cell interference can be written as a factor times S,

$$I_{sc} = \mathrm{K}_{\text{same}}\mathrm{S}, \tag{4a}$$

where $\mathrm{K}_{\text{same}} \approx 1$ for lack of specific information on multipaths [9]. The forward link power received from other base stations at a particular mobile's location acts as interference. This other-cell interference can also be written as a factor times S,

$$I_{oc} = \mathrm{K}_{\text{other}}\mathrm{S}, \tag{4b}$$

where $\mathrm{K}_{\text{other}} \approx 2.5\,\mathrm{dB} = 1.778$ near the cell edge [8]. Note that the factors K_{same} and $\mathrm{K}_{\text{other}}$ are defined by (4a) and (4b).

The total forward link interference power is denoted I_T , and we have

$$I_T = I_{sc} + I_{oc} = (\mathrm{K}_{\text{same}} + \mathrm{K}_{\text{other}})\,\mathrm{S} = \mathrm{K}_{\mathrm{f}}\mathrm{S}, \tag{4c}$$

where

$$\mathrm{K}_{\mathrm{f}} \triangleq \mathrm{K}_{\text{same}} + \mathrm{K}_{\text{other}}. \tag{4d}$$

B. Total Forward Link Transmitter Power

Having related the forward link interference power to the received signal power, we now develop the details of this received signal power. In doing so, we define a factor called the *forward link traffic channel power control factor,* denoted K_{traf}.

At the base station transmitter, the total power delivered by the power amplifier can be written as

$$\mathrm{P}_{\text{total}} = \mathrm{P}_1 + \mathrm{P}_2 + N_p\,\mathrm{P}_3 + \mathrm{K}_{\text{traf}} M\,\alpha_{\mathrm{f}}\,\mathrm{P}_4, \tag{5}$$

where

$$\begin{aligned}\mathrm{P}_j &= \text{power for channel category } j,\ j\text{=1, 2, 3, 4,}\\ N_p &= \text{number of active paging channels,}\\ M &= \text{number of active traffic channels,}\\ \alpha_{\mathrm{f}} &= \text{forward link voice activity factor,}\\ \mathrm{K}_{\text{traf}} &= \text{forward link power control factor.}\end{aligned}$$

The traffic channel transmitter power P_4 used in this formulation is taken to be the power transmitted for a mobile user at the cell edge. Note that in (5) the total traffic channel transmitted power is given by the term $\mathrm{K}_{\text{traf}} M\,\alpha_{\mathrm{f}}\,\mathrm{P}_4$. Although there are M active traffic channels, the total power in these channels is not $M\,\mathrm{P}_4$ because the (average) power for any channel is reduced by the average voice activity factor, $\alpha_{\mathrm{f}} \le 1$ [7]. In the same manner, the factor $\mathrm{K}_{\text{traf}} < 1$ in (5) is a parameter that takes into account the fact that most of the mobile users are not located at the cell edge, and assumes adaptive forward link power control by the base station.

If the forward link power for a particular traffic channel is adjusted to deliver the required median value of power to the mobile's location (and no more, to minimize interference), then it follows that the traffic channel power $\mathrm{P}_4\,(r)$ transmitted for a mobile at a distance r from the base station is inversely proportional to the propagation loss within the cell, and may be related to the power transmitted for a mobile at the cell edge (i.e., at distance $r = R$) by [9]

$$\mathrm{P}_4\,(r) = \mathrm{P}_4\,(R)\cdot\left(\frac{r}{R}\right)^{\gamma}. \tag{6a}$$

where γ is the propagation power law and R is the cell radius. If we assume that mobiles are equally likely to be at any distance r from the base station between the values $r = 0$ and $r = R$ (at the edge), then a pdf for the distance of mobiles from the base station can be written as the uniform distribution

$$\mathrm{p}_r\,(\alpha) = \begin{cases} 1/R, & 0 \le \alpha \le R,\\ 0, & \text{otherwise,}\end{cases} \tag{6b}$$

and the average traffic channel power is

$$\begin{aligned}\overline{\mathrm{P}}_4 &= \int_0^R \mathrm{P}_4\,(\alpha)\,\mathrm{p}_r\,(\alpha)\;d\alpha\\ &= \int_0^R \mathrm{P}_4\,(R)\left(\frac{\alpha}{R}\right)^{\gamma}\cdot\frac{1}{R}\,d\alpha\\ &= \mathrm{P}_4\,(R)\int_0^1 x^{\gamma}\,dx\\ &= \mathrm{P}_4\,(R)\cdot\frac{1}{\gamma+1}\\ &= \mathrm{P}_4\,(R)\cdot\mathrm{K}_{\text{traf}},\end{aligned} \tag{6c}$$

where

$$\mathrm{K}_{\text{traf}} = \frac{1}{\gamma + 1}, \quad \text{mobiles uniformly distributed over distance.} \tag{6d}$$

Because the power law is commonly between $\gamma = 3$ and $\gamma = 4$, a value of K_{traf} on the order of 0.2 or 0.3 would be reasonable, and $\mathrm{K}_{\text{traf}} = 0.5$ would be a conservative value. If, instead of being uniformly distributed in *distance* from the base station, the mobiles are uniformly distributed in *area* within the sector, then a pdf for the locations (r, θ) of mobiles within the sector is

$$\mathrm{p}_{r,\theta}(\alpha, \beta) = \begin{cases} \dfrac{2}{R^2\,\theta_s}, & 0 \le \alpha \le R,\ 0 \le \beta \le \theta_s, \\ 0, & \text{otherwise,} \end{cases} \tag{7a}$$

where θ_s is the sector angle. The average forward link traffic channel power is

$$\begin{aligned} \overline{\mathrm{P}}_4 &= \int_0^{\theta_s}\int_0^R \alpha\,\mathrm{P}_4(\alpha)\,\mathrm{p}_{r,\theta}(\alpha,\beta)\,d\alpha\,d\beta \\ &= \int_0^R \alpha\,\mathrm{P}_4(R)\left(\frac{\alpha}{R}\right)^{\gamma}\cdot\frac{2}{R^2}\,d\alpha \\ &= \mathrm{P}_4(R)\int_0^1 2x^{\gamma+1}\,dx \\ &= \mathrm{P}_4(R)\cdot\frac{2}{\gamma+2} \\ &= \mathrm{P}_4(R)\cdot\mathrm{K}_{\text{traf}}, \end{aligned} \tag{7b}$$

where

$$\mathrm{K}_{\text{traf}} = \frac{2}{\gamma+2} = \frac{1}{\frac{1}{2}\gamma + 1}, \quad \text{mobiles uniformly distributed over area.} \tag{7c}$$

A value of K_{traf} on the order of 0.3 or 0.4 would be reasonable for these assumptions, and $\mathrm{K}_{\text{traf}} = 0.5$ would still be a conservative value.

C. Net Losses on the Forward Link

We may define the forward link transmission loss L_T as the net loss on the link. Generalizing that definition to include not only antenna gains but the other loss factors for the forward link, we can write

$$\mathrm{L}_T(r) \triangleq \frac{\mathrm{L}(r)\cdot\mathrm{L}_{\text{rm}}\cdot\mathrm{L}_{\text{tc}}}{\mathrm{G}_m\cdot\mathrm{G}_c}, \tag{8a}$$

where

$\mathrm{L}(r)$ = link propagation loss at distance r,
L_{rm} = mobile receiver losses (cable, etc.),
L_{tc} = base station transmitter losses (cable, etc.),
G_m = mobile antenna gain,
G_c = base station antenna gain.

Given the total power delivered by the base station transmitter's power amplifier, the received power at the location of a mobile on the cell edge, in the absence of interference, is $\mathrm{P}_{\text{total}}/\mathrm{L}_T(R)$. Because the losses and gains are common to all the channels, the received channel powers to be used in calculating the channel SNRs are

$$\mathrm{S}_j = \frac{\mathrm{P}_j}{\mathrm{L}_T(R)}, \quad j = 1, 2, 3, 4. \tag{8b}$$

Table 1. Nominal parameter values.

Channel category	Requirement	ρ_j	$(\mathrm{PG})_j$
pilot($j = 1$)	$\left(\frac{\mathrm{E}_c}{\mathcal{N}_{0,T}}\right)_1 \ge \rho_1$	-15 dB	1 (0 dB)
sync($j = 2$)	$\left(\frac{\mathrm{E}_b}{\mathcal{N}_{0,T}}\right)_2 \ge \rho_2$	6 dB	1024 (30 dB)
paging($j = 3$)	$\left(\frac{\mathrm{E}_b}{\mathcal{N}_{0,T}}\right)_3 \ge \rho_3$	6 dB	256 (24 dB)
traffic($j = 4$)	$\left(\frac{\mathrm{E}_b}{\mathcal{N}_{0,T}}\right)_4 \ge \rho_4$	7 dB	128 (21 dB)

D. Solution for Forward Link Powers

With the preceding background and definitions, we now can solve for the powers P_1, P_2, P_3, and P_4 that will satisfy the constraints placed on the total transmitter power and the link budget for each forward link channel. Our formulation for this problem starts with the zero-margin case, then is extended to the general case of nonzero margin. The zero-margin constraints are the following:

$$\mathrm{P}_{\text{total}} = \mathrm{P}_1 + \mathrm{P}_2 + N_p\,\mathrm{P}_3 + \mathrm{K}_{\text{traf}}\,M\alpha_{\text{f}}\,\mathrm{P}_4 \le \mathrm{P}_{\text{max}}, \tag{9a}$$

$$\begin{aligned} \left(\frac{\mathrm{E}_b}{\mathcal{N}_{0,T}}\right)_j &= \frac{(\mathrm{PG})_j\,\mathrm{S}_j}{N_m + I_T} \\ &= \frac{(\mathrm{PG})_j\,\mathrm{P}_j}{N_m\mathrm{L}_T(R) + \mathrm{K}_{\text{f}}\,\mathrm{P}_{\text{total}}} \ge \rho_j, \end{aligned} \tag{9b}$$

where the $\{\rho_j\}$are the required values of the $\left\{(\mathrm{E}_b/\mathcal{N}_{0,T})_j\right\}$, as indicated in Table 1, along with nominal parameter values for CDMA cellular and PCS systems. Note that the constraint in (9b) is formulated for a mobile at the cell edge (distance R). Since the actual power for a particular traffic channel is assumed to be dynamically controlled, (9b) in the case of $j = 4$ pertains to the maximum value of P_4 that would be required, which might be used as an initial value for a traffic channel's power until the system's power control mechanism begins to adjust it to the level appropriate for the actual distance of the mobile from the base station.

If the inequality in (9b) is made an equality, it is clear that the solution, if one exists, will be the minimum required value of the transmitted power, P_j, since the partial derivative of the left hand side of (9b) with respect to P_j is always positive. It is possible that there is no joint solution for the transmitter powers that satisfies both (9a) and (9b), which may be seen by considering that $(\mathrm{E}_b/\mathcal{N}_{0,T})_j$ in (9b) has an upper bound given by

$$\frac{(\mathrm{PG})_j\,\mathrm{P}_j}{N_m\mathrm{L}_T(R) + \mathrm{K}_{\text{f}}\,\mathrm{P}_{\text{total}}} < \frac{(\mathrm{PG})_j}{\mathrm{K}_{\text{f}}}\cdot\frac{\mathrm{P}_j}{\mathrm{P}_{\text{total}}}. \tag{9c}$$

This bound is approached when $\mathrm{K}_{\text{f}}\,\mathrm{P}_{\text{total}} \gg N_m\mathrm{L}_T(R)$, a condition that may not satisfy (9a). Or, due to a high number of mobile users, the bound may be less than ρ_j for some j, thereby guaranteeing that (9b) is not satisfied.

Assuming that the power limitation (9a) is satisfied, as it should be in practice due to the proper selection of an amplifier power rating, and assuming that (9b) is made an equality instead of an inequality, the four cases of (9b) can be put in the form of a system of simultaneous equations to be solved for the channel powers; in matrix form, we have

$$\begin{bmatrix} a_1-1 & -1 & -N_p & -\mathrm{K_{traf}}\,M\alpha_\mathrm{f} \\ -1 & a_2-1 & -N_p & -\mathrm{K_{traf}}\,M\alpha_\mathrm{f} \\ -1 & -1 & a_3-N_p & -\mathrm{K_{traf}}\,M\alpha_\mathrm{f} \\ -1 & -1 & -N_p & a_4-\mathrm{K_{traf}}\,M\alpha_\mathrm{f} \end{bmatrix} \begin{bmatrix} \mathrm{P}_1 \\ \mathrm{P}_2 \\ \mathrm{P}_3 \\ \mathrm{P}_4 \end{bmatrix} = \begin{bmatrix} b \\ b \\ b \\ b \end{bmatrix} \tag{10a}$$

where

$$a_j \triangleq \frac{(\mathrm{PG})_j}{\rho_j\,\mathrm{K_f}}, \quad j\text{=1, 2, 3, 4,} \tag{10b}$$

and

$$b \triangleq \frac{N_m \mathrm{L}_T\,(R)}{\mathrm{K_f}} > 0. \tag{10c}$$

We now consider a generalization of these equations to include margins. A margin M_j (dB) for channel category j may be included in the analysis by stipulating that the SNRs (in dB) exceed their "required" values by some amount, resulting in the new SNR requirements given by

$$\rho_j'\,(\mathrm{dB}) \triangleq \rho_j\,(\mathrm{dB}) + \mathrm{M}_j\,(\mathrm{dB})\,, \quad j\text{=1, 2, 3, 4,} \tag{11a}$$

or

$$\rho_j' \triangleq \rho_j \cdot 10^{\mathrm{M}_j\,(\mathrm{dB})/10}, \quad j\text{=1, 2, 3, 4.} \tag{11b}$$

Thus, the quantities a_1 , a_2 , a_3 , and a_4 defined above now become, for the general case including margins:

$$a_j' = \frac{(\mathrm{PG})_j}{10^{\mathrm{M}_j\,(\mathrm{dB})/10}\rho_j\,\mathrm{K_f}} = \frac{(\mathrm{PG})_j}{\rho_j'\,\mathrm{K_f}}, \quad j\text{=1, 2, 3, 4.} \tag{11c}$$

Using the parameters $\{a_j'\}$ in (10a) in place of the $\{a_j\}$, the solutions for the four channel transmitter powers are [9], [10]

$$\mathrm{P}_j\,(\mathrm{K_f}, \mathrm{M}_j\,(\mathrm{dB})) = \frac{N_m\,\rho_j'\,\mathrm{L}_T\,(R)\,/(\mathrm{PG})_j}{1-\mathrm{K_f}\left[\rho_1' + \frac{\rho_2'}{(\mathrm{PG})_2} + N_p\frac{\rho_3'}{(\mathrm{PG})_3} + \mathrm{K_{traf}}\,M\alpha_\mathrm{f}\frac{\rho_4'}{(\mathrm{PG})_4}\right]}, \quad j\text{=1, 2, 3, 4.} \tag{12}$$

Note from these equations that the solution for each channel's required power is a function of not only the SNR requirements for all the channels, but also the data rates of all the forward link channels in terms of the processing gain of each channel. This means that the channel power requirements are interdependent. Note also that each channel power is a function of the number of active users M, which implies that ideally the forward link powers must be controlled in real time (dynamic power allocation) by using feedback involving all the parameters indicated in the denominators of the equations.

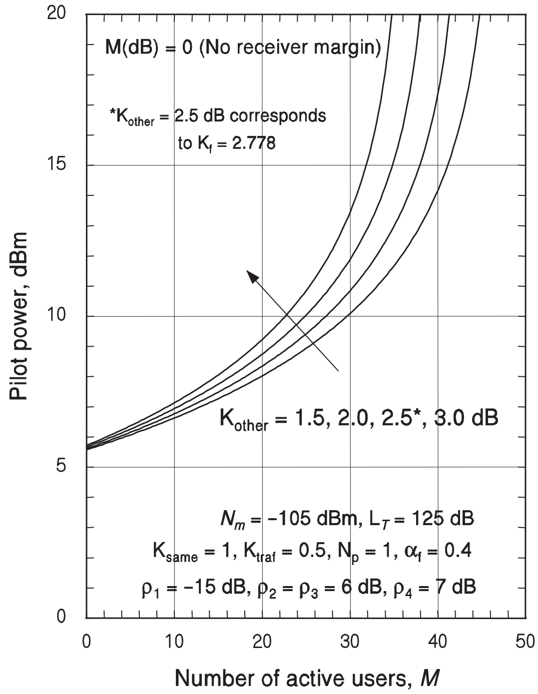

Fig. 2. P_1 *vs.* M for $\mathrm{K_{other}} = 1.5,\,2.0,\,2.5,\,3.0\mathrm{dB}$ and $\mathrm{M(dB)} = 0$, $N_m = -105\mathrm{dBm}$, $\mathrm{L}_T = 125\mathrm{dB}$, $\mathrm{K_{same}} = 1$, $\mathrm{K_{traf}} = 0.5$, $N_p = 1$, $\alpha_\mathrm{f} = 0.4$, $\rho_1 = -15\mathrm{dB}$, $\rho_2 = \rho_3 = 6\mathrm{dB}$, $\rho_4 = 7\mathrm{dB}$.

Because the forward link transmitter power for each of the four channel types varies by the same proportion for fixed SNR requirements, the general behavior of the power solutions can be observed using calculations of just the pilot channel transmitter power, $\mathrm{P}_1 \equiv \mathrm{P_{pilot}}$. For convenience, we assume that the same margin is used on each channel. That is, we assume that M_j (dB) in (11a) equals M(dB) for all the channels.

Let us now observe the functional behavior of P_1 versus M. Assuming $\mathrm{K_{same}} = 1$, the total interference factor is $\mathrm{K_f} = 1+\mathrm{K_{other}}$. In Fig. 2, we show pilot power as a function of the number of active users, M, with $\mathrm{K_{other}}$ varied from 1.5 to 3.0 dB in steps of 0.5 dB, assuming zero margin and the following parameter values: $N_m = -105$ dBm,[2] $\mathrm{L}_T = 125$ dB, $\mathrm{K_{traf}} = 0.5$, $N_p = 1$, and $\alpha_\mathrm{f} = 0.4$, in addition to the SNR requirements shown in Table 1. From (8), the assumed value of transmission loss is equivalent to a propagation loss of about 136 dB if it is assumed that $\mathrm{L_{tc}} = 2$ dB, $\mathrm{L_{rm}} = 3$ dB, $\mathrm{G}_c = 14.1$ dB, and $\mathrm{G}_m = 2.1$ dB [11]; in turn, a propagation loss of 136 dB is equivalent to a cellular radius of 2 to 3 km at cellular frequencies and 1 to 2 km at PCS frequencies [12]. We see in this figure

[2] This noise is based on a bandwidth of $W = 1.2288$ MHz, an 8 dB noise figure (NF), and an operating temperature of $T = 293\,^\circ$ K, so that $N_m = k\mathrm{TF}W$, with Boltzmann's constant $k = 1.38 \times 10^{-23}$ J/Hz/deg and $\mathrm{F} = 10^{\mathrm{NF}/10}$.

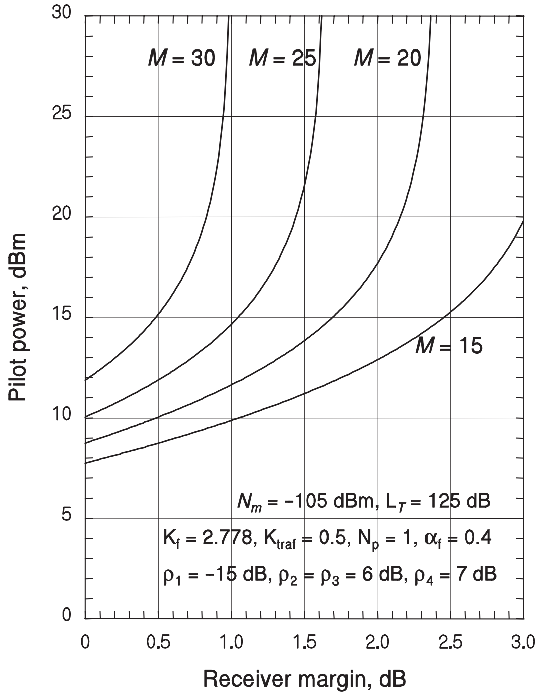

Fig. 3. P_1 $vs.$ $\mathrm{M(dB)}$ for $M = 15, 20, 25$, and 30 and $N_m = -105\mathrm{dBm}$, $\mathrm{L}_T = 125\mathrm{dB}$, $\mathrm{K_f} = 2.778$, $\mathrm{K_{traf}} = 0.5$, $N_p = 1$, $\alpha_{\mathrm{f}} = 0.4$, $\rho_1 = -15\mathrm{dB}$, $\rho_2 = \rho_3 = 6\mathrm{dB}$, $\rho_4 = 7\mathrm{dB}$.

that the transmitter power increases with the amount of other-cell interference, as indexed by $\mathrm{K_{other}}$, and that there is a value of M at which the required pilot power goes to infinity. For example, when $\mathrm{K_{other}} = 2.5\,\mathrm{dB}$, a typical value [9], the pilot power required to meet system requirements increases without limit as M approaches 39; thus, the effective capacity for this case is at most $M = 39$. For a system that is not heavily loaded ($M < 25$), the sensitivity of P_1 to $\mathrm{K_{other}}$ can be characterized as follows: a half-dB increase in $\mathrm{K_{other}}$ requires at most a half-dB increase in P_1; that is, the required increase in pilot power in this instance is less than an increase in the other-cell interference factor.

Fig. 3 shows the required pilot power as a function of the receiver margin, $\mathrm{M(dB)}$, for $M = 15$, 20, 25, and 30, and the same values of $\mathrm{K_f}$, $\mathrm{K_{traf}}$, N_p, α_{f}, ρ_1, ρ_2, ρ_3, and ρ_4 as in Fig. 2. It is important to note from the figure that, for a given user capacity, there is a limit for the system reliability that can be achieved because one cannot increase margin arbitrarily for higher reliability. For example, for $M = 30$ users, the system reliability cannot be increased by having a margin greater than 1 dB, which is the limit on the margin for a user capacity of $M = 30$. The same observation can be for the case of other capacity requirements, as shown in Fig. 3.

E. Channel Powers as Fractions of Total Power

The fraction of allocated power, ζ_j, for channel category j, is given by

$$\zeta_j \triangleq \frac{\mathrm{P}_j}{\mathrm{P_{total}}} = \frac{\rho_j'/\left(\mathrm{PG}\right)_j}{\rho_1' + \frac{\rho_2'}{\left(\mathrm{PG}\right)_2} + N_p\frac{\rho_3'}{\left(\mathrm{PG}\right)_3} + \mathrm{K_{traf}}\,M\alpha_{\mathrm{f}}\frac{\rho_4'}{\left(\mathrm{PG}\right)_4}}, \quad j=1, 2, 3, 4. \tag{13a}$$

When the margins are equal in all the channels (i.e., $\mathrm{M}_j\,(\mathrm{dB}) = \mathrm{M(dB)}$ for all j), then (13a) becomes

$$\zeta_j = \frac{\rho_j/\left(\mathrm{PG}\right)_j}{\rho_1 + \frac{\rho_2}{\left(\mathrm{PG}\right)_2} + N_p\frac{\rho_3}{\left(\mathrm{PG}\right)_3} + \mathrm{K_{traf}}\,M\alpha_{\mathrm{f}}\frac{\rho_4}{\left(\mathrm{PG}\right)_4}}, \quad j=1, 2, 3, 4, \tag{13b}$$

which is independent of the margin. Also note that the fractions do not depend on the interference factor $\mathrm{K_f}$ or on the transmission loss $\mathrm{L}_T\,(R)$, although the amount of power is very sensitive to these parameters. The fraction for a particular channel is primarily a function of the number of active users M, although it is also a function of the number of paging channels N_p. Note that the fraction of transmitter power allocated to the pilot or any other channel is not fixed but is inversely proportional to M; however, the pilot power itself increases with M, as seen from the form of (12).

III. RELATION BETWEEN TRANSMITTER AND RECEIVER MARGINS

Let us assume that forward link channel j has the receiver margin requirement $\mathrm{M}_j\,(\mathrm{dB})$, and let the margin at the receiver for a channel in absolute units (not dB) be denoted by Γ_{rj}, where

$$\mathrm{M}_j\,(\mathrm{dB}) = 10\log_{10}\Gamma_{rj}\left(\mathrm{K_f}\right), \quad j=1, 2, 3, 4, \tag{14a}$$

or

$$\Gamma_{rj}\left(\mathrm{K_f}\right) \triangleq 10^{\mathrm{M}_j\,(\mathrm{dB})/10}, \quad j=1, 2, 3, 4, \tag{14b}$$

and the argument $\mathrm{K_f}$ in $\Gamma_{rj}\left(\mathrm{K_f}\right)$ is a notation indicating that the margin depends on interference conditions. Now, let a transmitter "margin" or excess power ratio for channel j, corresponding to the receiver margin, be defined as

$$\Gamma_{tj}\left(\mathrm{K_f}\right) \triangleq \frac{\mathrm{P}_j\left(\mathrm{K_f},\,\mathrm{M}_j\,(\mathrm{dB})\right)}{\mathrm{P}_j\left(\mathrm{K_f} = 0,\,\mathrm{M}_j\,(\mathrm{dB}) = 0\right)}, \quad j=1, 2, 3, 4. \tag{15a}$$

The quantity in (15a) is the amount by which the transmitter power for the channel must be increased either to implement a receiver margin, to overcome interference, or both. Substituting (11b), (12), and (14a) in (15a), we can write (15b) shown at the bottom of the next page. If the receiver margins are all equal to $\Gamma_{rj} = \Gamma_r$, then from (15b) we observe that all the transmitter margins are equal to $\Gamma_{tj} = \Gamma_t$, and solving (15b) for the receiver margin results in the expression (16) shown at the bottom of the next page.

It is evident from (15b) and (16) that, in general, the transmitter margin must exceed the desired receiver margin, but when $\mathrm{K_f} = 0$ (no interference), they are equal. This fact is illustrated

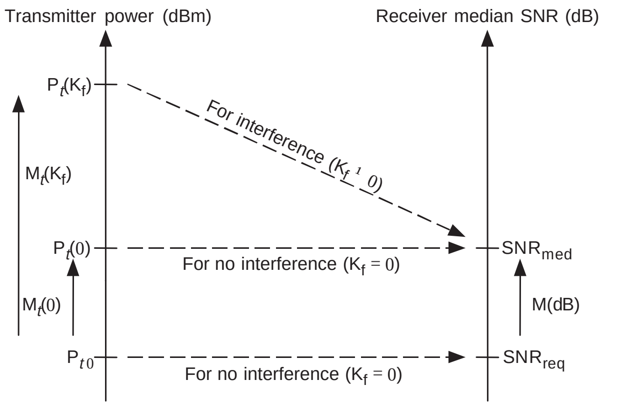

Fig. 4. Relationship between transmitter and receiver margins, without interference ($\mathrm{K_f} = 0$) and with interference ($\mathrm{K_f} > 0$).

qualitatively in Fig. 4. Calculations of (16) are plotted in Fig. 5 for the parameter values used in the previous figures (except $\alpha_\mathrm{f} = 0.45$) and for $M = 5$ to 30 in steps of 5. We see in Fig. 5 that some values of receiver margin for given reliability requirements may be unattainable no matter how much transmitter power is used, depending on M. The amount of receiver margin needed to attain a specified link reliability is found in Section IV.

The required amount of forward link power, as expressed in (12) and observed in Figs. 2 and 3, "blows up" at some value of M because each channel's power has a singularity as M approaches some value. This behavior can be interpreted as a limit to the forward link user capacity. In practice, the transmitter power is limited to $\mathrm{P_{max}}$, as expressed in the constraint given in (9a). Substituting (12) in (9a) and assuming each channel has the same margin leads to an upper bound on M that can be termed the *power-limited capacity*, denoted $M\left(\mathrm{P_{max}}\right)$:

$$M \le M\left(\mathrm{P_{max}}\right) \triangleq \frac{(\mathrm{PG})_4}{\mathrm{K_{traf}}\,\alpha_\mathrm{f}\,\rho_4}\left[\frac{10^{-\mathrm{M(dB)}/10}}{\mathrm{K_f} + N_m \mathrm{L}_T/\mathrm{P_{max}}} - \rho_1 - \frac{\rho_2}{(\mathrm{PG})_2} - N_p\frac{\rho_3}{(\mathrm{PG})_3}\right]. \tag{17a}$$

For no limit to the power ($\mathrm{P_{max}} \to \infty$), this bound becomes the inequality

$$M < M_\infty \triangleq \frac{(\mathrm{PG})_4}{\mathrm{K_{traf}}\,\alpha_\mathrm{f}\,\rho_4}\left[\frac{10^{-\mathrm{M(dB)}/10}}{\mathrm{K_f}} - \rho_1 - \frac{\rho_2}{(\mathrm{PG})_2} - N_p\frac{\rho_3}{(\mathrm{PG})_3}\right], \tag{17b}$$

in which M_∞ denotes the *forward link asymptotic capacity*. In view of (14a), we note that the first term of M_∞ can be written

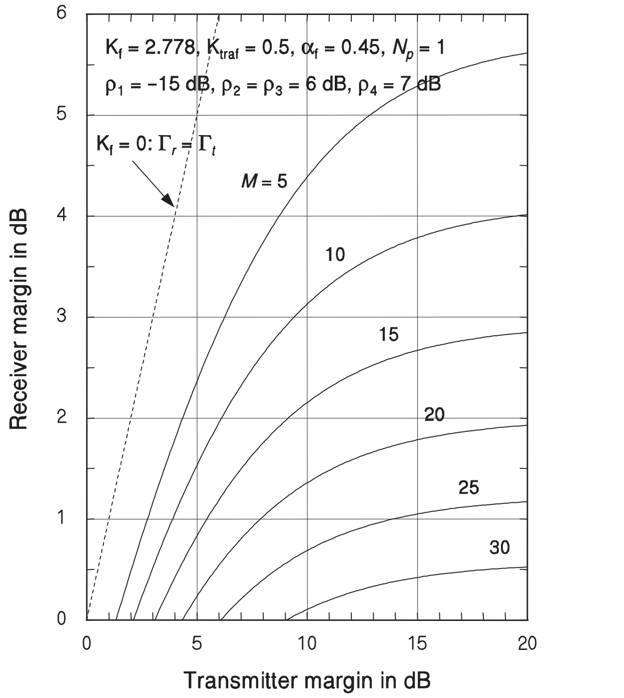

Fig. 5. Receiver margin $vs.$ transmitter margin for M=5, 10, 15, 20, 25, and 30 and $N_m = -105\mathrm{dBm}$, $\mathrm{K_f} = 2.778$, $\mathrm{K_{traf}} = 0.5$, $N_p = 1$, $\alpha_\mathrm{f} = 0.45$, $\rho_1 = -15\mathrm{dB}$, $\rho_2 = \rho_3 = 6\mathrm{dB}$, $\rho_4 = 7\mathrm{dB}$.

$$\frac{(\mathrm{PG})_4\,10^{-\mathrm{M(dB)}/10}}{\mathrm{K_f}\,\mathrm{K_{traf}}\,\alpha_\mathrm{f}\,\rho_4} = \left[\frac{W/R_b}{(\mathrm{E}_b/\mathcal{N}_{0,T})_{req}}\cdot\frac{1}{\alpha_\mathrm{f}}\cdot\frac{1}{\mathrm{K_f}\,\mathrm{K_{traf}}}\right]\cdot\frac{1}{\Gamma_r}. \tag{17c}$$

We observe from (17c) that the forward link capacity is inversely proportional to the receiver margin—any increase in margin for increasing link reliability has the cost of reducing user capacity.

In Fig. 6 we plot M_∞ and $M\left(\mathrm{P_{max}} = 1\,\mathrm{W}\right)$ as functions of the margin in dB, with the specific parameter assumptions used previously. The figure shows that the capacity is inversely proportional to the forward link power control factor $\mathrm{K_{traf}}$ and decreases rather quickly as the receiver margin increases. Note that the capacity decreases to one-half of its value for zero margin when the margin is about $2.5\,\mathrm{dB}$. Fig. 6 also demonstrates the sensitivity of the power solutions to the assumed value of $\mathrm{K_{traf}}$, just as Fig. 2 showed the effect of variations in the assumed value of $\mathrm{K_{other}}$. In [9], methods are discussed for implementing forward link power solutions using measurements instead of such assumptions.

$$\Gamma_{tj}\left(\mathrm{K_f}\right) = \frac{\Gamma_{rj}\left(\mathrm{K_f}\right)}{1 - \mathrm{K_f}\left[\Gamma_{r1}\left(\mathrm{K_f}\right)\rho_1 + \frac{\Gamma_{r2}\left(\mathrm{K_f}\right)\rho_2}{(\mathrm{PG})_2} + N_p\frac{\Gamma_{r3}\left(\mathrm{K_f}\right)\rho_3}{(\mathrm{PG})_3} + \mathrm{K_{traf}}\,M\alpha_\mathrm{f}\frac{\Gamma_{r4}\left(\mathrm{K_f}\right)\rho_4}{(\mathrm{PG})_4}\right]},\quad j{=}1, 2, 3, 4. \tag{15b}$$

$$\Gamma_r\left(\mathrm{K_f}\right) = \frac{\Gamma_t\left(\mathrm{K_f}\right)}{1 + \mathrm{K_f}\,\Gamma_t\left(\mathrm{K_f}\right)\left[\rho_1 + \frac{\rho_2}{(\mathrm{PG})_2} + N_p\frac{\rho_3}{(\mathrm{PG})_3} + \mathrm{K_{traf}}\,M\alpha_\mathrm{f}\frac{\rho_4}{(\mathrm{PG})_4}\right]} \tag{16}$$

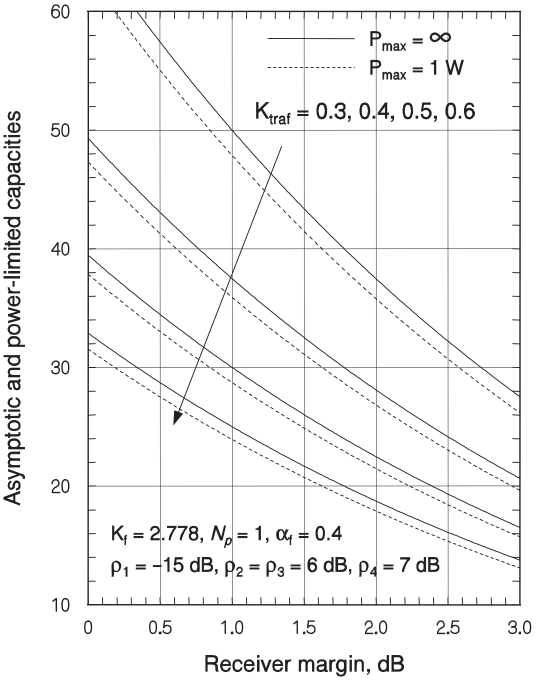

Fig. 6. Forward link power-limited and asymptotic capacities $vs.$ fade margin, for $\mathrm{K_{traf}} = 0.3, 0.4, 0.5,$ and 0.6 and $N_m = -105\mathrm{dBm}$, $\mathrm{K_f} = 2.778$, $\mathrm{K_{traf}} = 0.5$, $N_p = 1$, $\alpha_f = 0.4$, $\rho_1 = -15\mathrm{dB}$, $\rho_2 = \rho_3 = 6\mathrm{dB}$, $\rho_4 = 7\mathrm{dB}$, and $\mathrm{P_{max}} = 1\mathrm{W}$.

IV. FORWARD LINK RELIABILITY AS A FUNCTION OF MARGIN

In (2a) we expressed the reliability of the jth forward link channel as the probability that the received SNR at a mobile near the cell edge exceeds the SNR requirement for that channel. Substituting the channel power solutions into the expression for $(\mathrm{SNR})_j$, we obtain

$$P_{rel}(j) \triangleq \Pr\left\{(\mathrm{SNR})_j = \frac{\mathrm{P}_j/\mathrm{L}_T(R)}{N_m + \mathrm{K_f\,P_{total}}/\mathrm{L}_T(R)} > \frac{\rho_j}{(\mathrm{PG})_j}\right\}, \quad j=1,2,3,4, \tag{18}$$

in which the random variable is the net link loss, $\mathrm{L}_T(R)$. Note that, unlike in (2c), we now include multiple-access interference in the SNR expression. Since we are modeling same-cell and other-cell interference as a factor times the received forward link power, the propagation loss affects the interference as well as the signal. With regard to fluctuations in that loss, it is reasonable to assume that the same-cell interference is subject to the same fluctuations, while the fluctuations in the propagation loss experienced by the other-cell interference may be different, although correlated because the transmissions share the same receiver location. We analyze the case of identical fluctuations in propagation losses experienced by same-cell and other-cell interference.

A. Same Other-Cell Fluctuations

We assume for this case that the shadowing experienced by the other-cell interference is modeled by the same random component of the propagation loss. In terms of the loss, the reliability then can be written

$$P_{rel}(j) = \Pr\left\{\mathrm{L}_T(R) < \frac{\mathrm{P}_j(\mathrm{PG})_j/\rho_j - \mathrm{K_f\,P_{total}}}{N_m}\right\}, \quad j=1,2,3,4. \tag{19}$$

The expression in (19) is based on the fact that, unlike on the reverse link (on which each channel has a different random propagation loss), the forward link channel powers arriving at a particular mobile's location all have precisely the same propagation loss, since there are transmitted simultaneously on the same RF carrier. Note in (18) that if the thermal noise term N_m is neglected, the received SNR does not depend on $\mathrm{L}_T(R)$. However, if the interference term $\mathrm{K_f\,P_{total}}/\mathrm{L}_T(R)$ is neglected, the received SNR is directly proportional to the inverse of $\mathrm{L}_T(R)$. The general case is between these two extremes, so that the size of the fluctuations in the SNR is generally smaller than the fluctuations in the loss.

For a lognormal propagation loss as modeled in (1a), the net transmission loss to the cell edge can be expressed as $\mathrm{L}_T(\mathrm{dB}) = \mathrm{L}_{Tmed}(\mathrm{dB}) + \sigma_{dB}\mathrm{G}(0,1)$. In absolute units, we may write

$$\begin{aligned}\mathrm{L}_T(R) &= 10^{(\mathrm{L}_{Tmed}(\mathrm{dB})+\sigma_{dB}\mathrm{G}(0,1))/10}\\ &= (\mathrm{L}_T(R))_{med}\cdot 10^{\sigma_{dB}\mathrm{G}(0,1)/10}.\end{aligned} \tag{20}$$

Substituting (20) in (19) leads to the result (21a) shown at the bottom of the page. If we assume that the net loss in the power solutions (12) is the median value of that loss, we have

$$\mathrm{P}_j = \frac{N_m\,\Gamma_r\rho_j\,(\mathrm{L}_T(R))_{med}/(\mathrm{PG})_j}{1 - \mathrm{K_f}\,\Gamma_r\left[\rho_1 + \frac{\rho_2}{(\mathrm{PG})_2} + N_p\frac{\rho_3}{(\mathrm{PG})_3} + \mathrm{K_{traf}}\,M\alpha_{\mathrm{f}}\frac{\rho_4}{(\mathrm{PG})_4}\right]}. \tag{21b}$$

Substituting (21b) and (9a) into (21a), we obtain

$$P_{rel} = \Pr\left\{\mathrm{G}(0,1) < \frac{\mathrm{M}_L(\mathrm{dB})}{\sigma_{dB}}\right\} = 1 - \mathrm{Q}\left(\frac{\mathrm{M}_L(\mathrm{dB})}{\sigma_{dB}}\right), \tag{22}$$

where $\mathrm{Q}(x)$ is the Gaussian Q-function and the quantity $\mathrm{M}_L(\mathrm{dB})$, a "loss margin," is given by

$$\mathrm{M}_L(\mathrm{dB}) \triangleq 10\log_{10}\Gamma_L, \tag{23a}$$

$$\begin{aligned}P_{rel}(j) &= \Pr\left\{(\mathrm{L}_T(R))_{med}\cdot 10^{\sigma_{dB}\mathrm{G}(0,1)/10} < \frac{\mathrm{P}_j(\mathrm{PG})_j/\rho_j - \mathrm{K_f\,P_{total}}}{N_m}\right\}\\ &= \Pr\left\{\mathrm{G}(0,1) < \frac{10}{\sigma_{dB}}\log_{10}\left(\frac{\mathrm{P}_j(\mathrm{PG})_j/\rho_j - \mathrm{K_f\,P_{total}}}{N_m(\mathrm{L}_T(R))_{med}}\right)\right\}, \quad j=1,2,3,4.\end{aligned} \tag{21a}$$

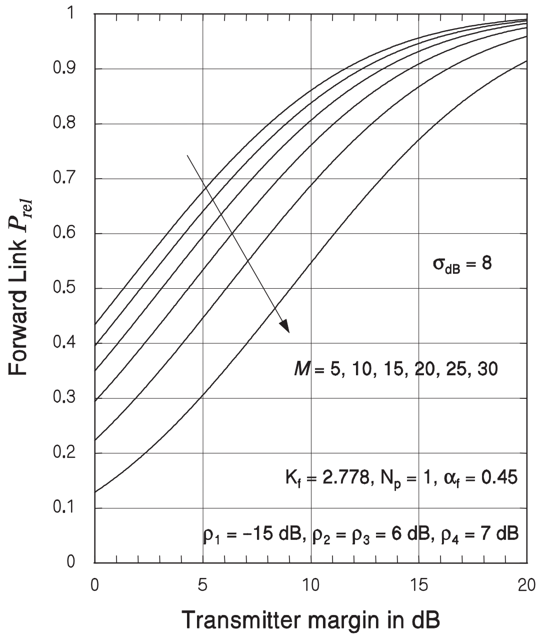

Fig. 7. Forward link reliability $vs.$ transmitter margin for M=5, 10, 15, 20, 25, and 30 and $\mathrm{K_f} = 2.778$, $\mathrm{K_{traf}} = 0.5$, $N_p = 1$, $\alpha_\mathrm{f} = 0.45$, $\rho_1 = -15\mathrm{dB}$, $\rho_2 = \rho_3 = 6\mathrm{dB}$, $\rho_4 = 7\mathrm{dB}$.

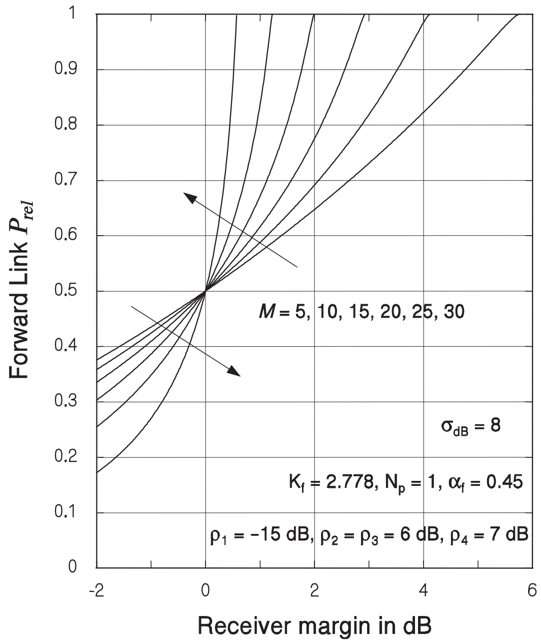

Fig. 8. Forward link reliability $vs.$ receiver margin for M=5, 10, 15, 20, 25, and 30 and $\mathrm{K_f} = 2.778$, $\mathrm{K_{traf}} = 0.5$, $N_p = 1$, $\alpha_\mathrm{f} = 0.45$, $\rho_1 = -15\mathrm{dB}$, $\rho_2 = \rho_3 = 6\mathrm{dB}$, $\rho_4 = 7\mathrm{dB}$.

where

$$\Gamma_L = \frac{\Gamma_r - \mathrm{K_f}\Gamma_r\left[\rho_1 + \frac{\rho_2}{(\mathrm{PG})_2} + N_p\frac{\rho_3}{(\mathrm{PG})_3} + \mathrm{K_{traf}}M\alpha_\mathrm{f}\frac{\rho_4}{(\mathrm{PG})_4}\right]}{1 - \mathrm{K_f}\Gamma_r\left[\rho_1 + \frac{\rho_2}{(\mathrm{PG})_2} + N_p\frac{\rho_3}{(\mathrm{PG})_3} + \mathrm{K_{traf}}M\alpha_\mathrm{f}\frac{\rho_4}{(\mathrm{PG})_4}\right]} > \Gamma_r. \tag{23b}$$

Note that when the margins are assumed to be the same for all channels, they all have the same reliability, so the index j is omitted in (22). When the expression for Γ_r in (16) is substituted in (23b), we obtain Γ_L in terms of the transmitter margin, Γ_t:

$$\Gamma_L = \Gamma_t\left[1 - \mathrm{K_f}\left(\rho_1 + \frac{\rho_2}{(\mathrm{PG})_2} + N_p\frac{\rho_3}{(\mathrm{PG})_3} + \mathrm{K_{traf}}M\alpha_\mathrm{f}\frac{\rho_4}{(\mathrm{PG})_4}\right)\right] < \Gamma_t. \tag{24a}$$

Note that

$$\Gamma_r < \Gamma_L < \Gamma_t, \tag{24b}$$

which indicates that the receiver margin Γ_r for achieving a particular value of link reliability is less than the loss margin,

$$\Gamma_r < \Gamma_L \equiv 10^{\mathrm{M}_L(dB)/10} = 10^{\sigma_{dB}\cdot \mathrm{Q}^{-1}(1-P_{rel})/10}, \tag{25}$$

so that the achievable link reliability is not as severely limited as it seemed from the limitation on receiver margin shown previously in Fig. 5.

B. Numerical Results for Margins

What then, is the margin needed to accomplish a specific value of link reliability? Fig. 7 shows P_{rel} as a function of the transmitter margin in dB units, assuming that the standard deviation of the loss in dB units is $\sigma_{dB} = 8$. We observe in the figure that when the number of active users increases from $M = 5$ to $M = 30$, a 50% link reliability would requires a transmitter margin increase from 1.5 dB to 9.0 dB, while a 90% link reliability requires a transmitter margin increase from 11.5 dB to 19.3 dB. A plot of the reliability as a function of the receiver margin in dB is given in Fig. 8; it is interesting to note from Fig. 7 and Fig. 8 that, for a link reliability greater than 50%, transmitter margins that are increasing with M correspond to *decreasing* receiver margins for increasing M. The receiver margins are decreasing with M because the cochannel interference increases with M.

V. CONCLUSION

In this paper, we have presented the solutions for the minimum CDMA forward link transmitter powers for the specified channel bit error rate performance of each channel category for maximizing user capacity, in conjunction with fade margin requirements for achieving a specified level of link reliability. Our solutions provide the minimum interference power levels from each base station transmitter to users, not only in the same cell, but also in other adjacent cells. It is shown that the maximum capacity is inversely proportional to the margins that are used to increase link reliability. Optimum selections for the parameters in terms of transmitter powers, link reliability, and achievable user capacity can be found from the equations and graphical results provided in the paper, which are plots of the general solutions for typical values of the parameters.

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Jhong Sam Lee received the B.S.E.E. degree from the University of Oklahoma, Norman, OK, in 1959, and the M.S.E. and D.Sc. degree in electrical engineering from George Washington University, Washington, DC, in 1961 and 1967, respectively.

Dr. Lee has over 35 years of experience as an electronics systems engineer, a professor, and as a high technology business corporate executive. He is internationally known in the field of communications and information technology, and was elected a Fellow of the IEEE for his contributions to spread spectrum communications. From 1959 to 1964, he worked in the industry in radar systems and in microwave and millimeter wave component development.

From 1965 to 1968, he was an Assistant Professor of engineering and applied science at George Washington University, Washington, DC, where he taught courses in random processes, digital communication theory, coding, and information theory. From 1968 to 1969, he was an Advisory Engineer at IBM Corporation, Gaithersburg, MD, where he worked on military satellite communication systems. From 1969 to 1973, he was an Associate Professor of electrical engineering at the Catholic University of America, Washington, DC, where he taught detection and estimation theory, and communication and coding theories. From 1965 to 1973 he was Expert Consultant at the U.S. Naval Research Laboratory in the areas of underwater signal processing and spread spectrum communication systems. From 1973 to 1976 he was an Associate Director at the Magnavox Advanced Systems Analysis Office (ASAO), Silver Spring, MD, where he was engaged in NASA and Department of Defense satellite and communications programs. From 1976 to 1998, as Founder and President of J. S. Lee Associates, Inc., Rockville, MD, he directed and managed over 40 R& D programs in the areas of communication and electronic warfare systems. He was a Professorial Lecturer at George Washington University from 1982 to 1984. From 1985 to 1986, he was President and CEO of Dae Young Electronics Industrial Company, Ltd., Seoul, Korea. Since July 1, 1998, Dr. Lee has been the President and CEO of Hung Chang Co, Ltd., in Seoul, Korea, a manufacturer of precision instruments and wireless communications system components, such as linear power amplifiers (LPAs) and repeaters.

Dr. Lee has published over 70 papers in IEEE publications and he is co-author of *CDMA Systems Engineering Handbook* (Artech House, Boston, 1998).

Leonard E. Miller was born in Washington, DC, in 1942. He received the BEE degree from Rensselaer Polytechnic Institute, Troy, NY, in 1964; the MSEE degree from Purdue University, West Lafayette, IN, in 1966; and the PhD degree from The Catholic University of America, Washington, DC, in 1973.

While at Rensselaer, Dr. Miller worked as a co-op student at the General Electric Company, Syracuse, NY. From 1964 to 1978 he was with the Naval Surface Warfare Center, Silver Spring, MD, where he was a member of the Signal Processing Branch. Since 1978 he has been with J. S. Lee Associates, Inc., Rockville, MD, where he is Vice President for Research, and has been involved in research and development of communications systems in the areas of signal intelligence, satellite, and electronic warfare for the Department of Defense and its agencies. His recent interests include the modeling of propagation in the mobile environment and the design and analysis of CDMA cellular and personal communications systems.

Dr. Miller has published over 40 papers in IEEE publications and he is co-author of *CDMA Systems Engineering Handbook* (Artech House, Boston, 1998). Dr. Miller is a Senior Member of the IEEE.